BELLCOMM, INC.

SUBJECT: A Discussion of the Proposed Two Burn Lunar Orbit Insertion Maneuver
Case 310

DATE: August 5, 1968

FROM: D. A. Corey

ABSTRACT

Several of the arguments concerning the requirement for a two-burn lunar orbit insertion maneuver are discussed. In general, there appears to be no good technical argument either for or against the proposal. The monitoring limits for the one-burn LOI maneuver can be set so that both the probability of crashing and the probability of a premature engine shutdown are very small. There is a possibility that the duration of the lunar orbit timeline would be lengthened by four hours because of the two revolutions in the intermediate parking orbit. The author has not heard a strong argument that this is significantly detrimental, however.

(NASA-CR-73521) DISCUSSION OF THE PROPOSED TWO BURN LUNAR ORBIT INSERTION MANEUVER (Bellcomm, Inc.) 11 p

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MEMORANDUM FOR FILE

INTRODUCTION

MSC has recently proposed that the Apollo lunar orbit insertion (LOI) maneuver be done in two stages. The first maneuver would place the spacecraft into something like a 60 by 170 nautical mile elliptical parking orbit. After two complete orbits, a second maneuver would be performed placing the spacecraft into a 60 nautical mile circular orbit. The two orbits between maneuvers are provided to allow for MSFN tracking and a state vector and target update prior to the second maneuver. In addition, provision is currently being made to perform a plane trim maneuver about two and one quarter orbits after a one burn LOI or at about a quarter of an orbit after a two burn LOI. In the two burn case, the trim burn may be included in the second burn.

REASONS FOR THE TWO-BURN LOI

The MSC proposal is based primarily on the feeling that deboosting into Lunar Orbit is safer in that it would require a significantly longer overburn on the first maneuver to get the spacecraft into trouble. In the single burn case, an overburn of about 8.5 seconds (when applied in the most sensitive direction) results in a subsurface perilune. When deboosting into a 60 by 170 nautical mile orbit, an overburn of about 15 seconds is required for a subsurface perilune. MSC feels that the difference of 6.5 seconds provides an attractive extra safety margin.

MSC also offered some supporting arguments for the two-burn deboost. During the LOI maneuver, the astronauts will be monitoring the EMS (Entry Monitoring System) ΔV counter and the clock in order to prevent an overburn. If the ΔV counter and the clock exceed certain limits, the astronauts are to shut down the engine manually. A study (Reference 1) done at MSC indicated that with a particular strategy for selecting the clock and ΔV counter monitor limits, there is a significant probability that the astronauts will prematurely shut down the engine during a good G & N controlled maneuver.

This result is based on a study of the expected dispersions in LOI maneuver burn times and on the expected errors in the ΔV counter. If this happened, another maneuver would be required to complete the insertion into the 60 mile circular orbit. MSC contends that it would be better to plan on the second maneuver and make provision for it in the timeline. In fact, they argue, why not always make a second maneuver? If a second maneuver is scheduled, it can be made long enough to ensure that the guidance system gets control of it and steers out any attitude dispersions and center of gravity uncertainties existing at the beginning of the burn. (The center of gravity uncertainties should actually be quite small following the long first burn.) Subsequent study, however, has uncovered errors in the numbers presented in Reference 1. The probability of an underburn is actually significantly smaller than stated in Reference 1. Furthermore, this memorandum will demonstrate that it is possible to make the probability of an underburn even smaller while still ensuring a very high probability of a safe one-burn LOI.

MSC also contends that, since two orbits are required prior to the plane trim maneuver, the actual timeline is not really affected by the two orbits between the two LOI maneuvers. The second, or circularization, burn can be performed on the same orbit as the plane trim maneuver. In fact, analysis done here at Bellcomm and at MSC indicates that it is feasible to combine the circularization and plane trim maneuvers. The problem with this argument is that there are good reasons for not doing the plane trim maneuver so long before landing. (Current timelines place landing some 16 to 20 hours after LOI.) Previous studies (for example, Reference 2) indicate that the expected three sigma out-of-plane position errors after LOI are about 15,000 feet (not including navigation errors before LOI). This represents about .15 degree out-of-plane error on the lunar surface. A recent MIT study which included the effects of MSFN uncertainties prior to LOI indicates post LOI out-of-plane three sigma dispersions in the neighborhood of 0.4 to 0.5 degrees. An MSC study of Orbiter III data indicates that there is an uncertainty of about 0.3 degrees involved in MSFN determination and propagation of the out-of-plane spacecraft position in lunar orbit. The expected dispersions then, are only slightly larger than the uncertainty in determining them. Furthermore, considering the uncertainty in the lunar gravitational potential, there is enough dissimilarity between the Orbiter III orbit and the 60 mile circular Apollo parking orbit to at least raise the possibility that the 0.3 degree uncertainty may be optimistic.

The best way out of the dilemma, insofar as accurately adjusting the plane is concerned, is to do the plane trim as close to landing as possible. This would allow incorporation of data from optical sightings of the landing site. The difficulty arises when trying to find a place for the maneuver in the already overcrowded lunar orbit timeline. At this point, however, it would seem that there is a not insignificant probability that the optical sightings of the landing site will disclose a plane error greater than 0.3 degrees and force an unplanned CSM plane trim. (The current LM descent ΔV budget allows for 0.3 degrees plane correction.) This would argue that unless the lunar gravitation potential problem is solved or further analysis shows that no problem exists, allowance for the trim maneuver must be made in the timeline close to landing. The two-burn LOI proposal would then add an extra two orbits to the lunar orbit timeline. The plane trim close to landing might require an extra orbit on the landing day, but apparently there is a good chance another orbit will be required anyway because of the overcrowded timeline. If, on the other hand, it can be definitely shown that the plane trim can be satisfactorily performed on the LOI day, it would probably be better to do it then in order to avoid conflict with activity close to landing. In that case, the two-burn LOI does not force an increase in the time in lunar orbit.

It's true that the longer the mission, the smaller the chance of mission success. However, it is difficult to imagine that the extra four hours required by the two-burn LOI is significantly detrimental. The extra two orbits in the lunar orbit timeline could be critical on long flight time non-free return (maybe hybrid) trajectories because of LM system lifetime constraints. For free return flight times, however, the extra four hours is not a problem in this respect.

Still another argument for the operational superiority of the two burn deboost is that LM weight problems may force a requirement for an even lower parking orbit. It would seem, however, that if the parking orbit gets much lower than 60 miles, the resulting low approach hyperbola pericynthions might force one to use a three-burn deboost rather than a two- or one-burn deboost.

Another possible advantage to the two burn LOI is that it may be possible to perform the maneuver with a slightly more degraded G & N system than would be possible in the one burn case. This would not contribute to the probability of a successful lunar landing mission, but might mean that a lunar orbit mission could be performed rather than a simple flyby mission in certain cases.

PROBABILITY OF EARLY SHUTDOWN

At this point, it is useful to examine the probability of an early shutdown of an otherwise good burn. Reference 1 used the following method for selecting the monitor limits for the clock and the ΔV counter:

Monitor Limit = Nominal Value - 3σ Dispersion - Astronaut Delay + Bias.

The bias term represents the extra burn time or ΔV required to achieve a selected perilune altitude. For example, the extra ΔV required to change the orbit from 80 miles circular to an 80 by 40 mile ellipse is 55.6 fps. Selecting the monitor limit in this manner places the probability of achieving a perilune less than, in this example 40 miles, at the three sigma point (probability equals .00135) when monitoring each system. If the astronaut waits until both the ΔV counter and the clock exceed the monitor limits, the probability of a perilune less than 40 miles is .002698 (assuming the distributions are normal and independent).

The trajectory used in Reference 1 produced the statistics and nominal values shown in the following table.

	LOI Burn Time (sec)	ΔV Counter Reading at the End of LOI (fps)
Nominal	382.77	3169.8
Mean	382.80	3170.4
1σ	1.67	14.32
3σ	5.01	42.96
Low 3σ	377.76	3126.84
High 3σ	387.78	3212.76

The statistics were normally distributed with a high probability that the mean is equal to the nominal value. The value used for astronaut delay was 1 second (= 9.8 fps for the ΔV counter).

The authors were using a trajectory which involved insertion into an 80 nautical mile parking orbit. The numbers obtained for the 80 mile parking orbit were applied to a 60 mile parking orbit by making the approximation that the ΔV required to lower the perilune of a circular orbit by some ΔH (for example, 40 miles) was the same for both the 60 by 20 mile case and the 80 by 40 mile case.

The following tables are extracted from Reference 1.

Table 1

The Bias Values Used For The Clock And ΔV, Counter As A Function Of The Allowed Change In The Resulting Orbit, ΔH

H_a/H_p	(n. mi.)	80/50	80/40	80/30	80/20
ΔH	(n. mi.)	30	40	50	60
Bias	Clock	4.24	5.65	7.05	8.46
	ΔV Counter	41.7	55.6	69.4	83.3

The resulting monitor limits for the clock and EMS ΔV counter are presented in Table 2. Note that these include the astronaut delay factor.

Table 2

Monitor Limits for the Clock and ΔV Counter as a Function of ΔH

ΔH (n. mi.)	30	40	50	60
Clock (sec.)	381.0	382.4	383.8	385.2
ΔV Counter (ft/sec.)	3158.7*	3172.6*	3186.4*	3200.3*

In deriving the data for Tables 3 and 4, the Reference 1 authors determined the probability that the burn time or the ΔV counter reading for a good G & N burn exceeded the monitor limits presented in Table 2. This then, determines the probability

*These numbers were calculated by the author from the data in Reference 1 and each is smaller than the value presented in Reference 1 by 1.7 fps. The author talked with the authors of Reference 1 about the difference, but the reason for the discrepancy has not been resolved yet.

that a good G & N burn will be manually shut down prematurely. Since there is a finite probability that the G & N system will cause engine shutdown during the one-second astronaut delay period, the probabilities should have been computed on the basis of the monitor limit plus the astronaut delay allowance. This actually makes quite a difference. For example, Reference 1 presents the value of 24.8% as the probability of an under-burn for a bias based on a $\Delta H = 40$ miles and based on monitoring both systems. Taking the astronaut delay time into account yields a probability of 7% for this case. The following tables are equivalent to Tables 3 and 4 in Reference 1 but with the astronaut delay taken into account.

Table 3

Probability of Cutting Off a Good G & N Maneuver Based on Monitoring Both the EMS ΔV Counter and the Clock

ΔH (n. mi.)	30	40	50	60
% Probability	38.1	6.8	0.3	0

Table 4

Probability of Cutting Off a Good G & N Maneuver Based on Monitoring Either the EMS ΔV Counter Only or the Clock Only

ΔH (n. mi.)		30	40	50	60
% Probability	Clock	68	36	11	2
	EMS ΔV	56	19	2.5	0

Table 3 in Reference 1 was derived from actual examination of the Monte Carlo samples. Here, Table 3 was derived from the data in Table 4 and assumes the distributions are statistically independent. There is a very weak dependence of the ΔV counter on the burn time due to extra gravity losses in a longer burn. However, that extra ΔV is so much smaller than the ΔV counter errors that the figures wouldn't be affected for the number of significant digits presented (not to mention how accurately the author can read a xeroxed graph).

The Reference 1 study was not designed to produce information about the orbits that would result from the premature shutdown. For the $\Delta H = 40$ and monitoring both systems case, however, it would seem that a very large percentage of those 7% early shutdowns are very nearly in the desired orbit. The probability of having to do another maneuver to reduce apolune would seem to be quite small. Furthermore, the probability of crashing with those monitoring limits can be shown to be about 1.9×10^{-5} times the probability of a G & N failure which inhibits automatic shutdown, goes undetected by the astronaut watching the DSKY, FDAI, and monitor displays, but allows manual shutdown of the engine. To compute the probability of crashing, crashing was defined as exceeding the ΔV required to lower perilune of a circular orbit at the 3σ low post LOI perilune altitude (54 miles) to zero miles altitude. Thus, the monitor limits are seen to be extremely conservative. If the altitude dispersions for the 7% early shutdowns can not be tolerated, there is plenty of slack in the monitor limits.

As another example, the data in Reference 1 was reworked to remove the effects of the equivalence of the statistics for 80 mile and 60 mile parking orbits. Insertion into a 60 mile parking orbit requires in the neighborhood of 23.3 fps greater ΔV than does insertion into an 80 mile orbit. This represents about 2.38 seconds additional burn time. If one assumes that the expected one sigma dispersions increase proportionally to the extra ΔV, they become 14.425 fps and 1.68 sec. for the ΔV counter and the burn time respectively. If the monitor limits are set up the same way as in Reference 1 for the $\Delta H = 40$ mile case, they become 3194.9 fps* for the ΔV counter and 383.53 sec.* for the clock (including astronaut delay time). For these limits, the probability of an underburn is 66.64% monitoring the clock only, 21.19% monitoring the ΔV counter only, and 14.12% monitoring both systems. The probability of crashing is 2.87×10^{-7} monitoring the clock only, 5.41×10^{-6} monitoring the ΔV counter only, and 5.7×10^{-6} monitoring both systems. Again these should be multiplied by the probability of the G & N failure.

The monitor limits can also be selected to provide some given probability of an underburn. For example, if the desired probability of an underburn is set at 1% and the probability of an underburn due to monitoring each system individually is set at 10%, the probability of crashing can

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*These figures use 54.877 fps bias to get from 60 mile circular to a 60 by 20 mile ellipse.

be computed. Incidently, that breakdown of 10% to each system does not minimize the probability of crashing. A much better distribution can be found, but this one will serve as an example. The resulting monitor limits would be 388.3 seconds for the clock and 3221.4 fps for the ΔV counter. The probability of crashing is 4.83×10^{-4} monitoring the clock only, 3.17×10^{-5} monitoring the ΔV counter only and 4.44×10^{-4} monitoring both. The limits are still quite safe--especially when the probability of the G & N failure is included. The numbers are also conservative because they assume that the extra ΔV is applied in the most sensitive direction.

As a conclusion from all this, it does not appear that the monitoring problem contributes a requirement for a two-burn deboost--at least, not for injection into a 60 mile parking orbit. Direct injection into substantially lower orbits would be a different story.

SUMMARY AND CONCLUSION

Several of the arguments for the two-burn deboost have been discussed and none of them seem to indicate that it is required. The expected LOI dispersions do not indicate a requirement for it. Monitor limits can be established which are both safe and provide a very small probability of a premature shutdown. This is especially so when one considers the probability of a G & N failure which inhibits automatic shutdown, goes undetected by the astronauts watching the DSKY, FDAI, and monitor displays, but allows manual engine shutdown.

The argument that the timeline is not affected because of the two orbits in the intermediate parking orbit required before the plane trim maneuver is shaky because there is real doubt as to the usefulness of the plane trim that long before landing anyway. On the other hand, it is probable that the extra two orbits are not significantly detrimental.

Generally, then, there appears to be no good technical argument for the two-burn LOI. But, neither has one been brought up that indicates it should not be done. Unless it can be shown that a plane trim soon after LOI completely guarantees that another one won't be required shortly before landing, the two-burn LOI involves an extra CSM/RCS fuel expenditure.

Rigorously speaking, the two burn LOI does, in fact, decrease the probability of a crash, but the decrease is from an already very small probability. It is possible that an extra SPS burn would have some implication on the probability of mission success. If, however, only one plane trim is required, and if it can be accurately done in conjunction with the second LOI burn, no extra SPS maneuvers are involved.

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Subject: A Discussion of the Proposed Two Burn Lunar Orbit Insertion Maneuver

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